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Relationship of percolation stability of soil aggregates to land use, selected properties, structural indices and simulated rainfall erosion

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Abstract

Simple tests of structural stability are needed for evaluating the ease with which soils slake and erode when in contact with water. In a laboratory study, we related the percolation stability (PS) of 22 Nigerian soils to land use, soil properties, structural stability indices and simulated rainfall erosion. All measurements were carried out with the 1–2 mm diameter air-dry aggregates. Land use influenced PS more than the type of soil. Forest soils, bush fallows, mulched, minimally tilled plots and pasture lands had rapid PS (>250 ml/10 min) values, whereas mulched conventionally tilled plots, bare fallows and continuously cultivated plots from where residues were removed by burning had relatively slow to moderate PS values (34–241 ml/10 min). The single most important soil property that correlated positively with PS is organic matter (OM) ($r = 0.55^{*}$) followed by total Fe + Al ($r = 0.52^{*}$). The significant inverse relationship ($r = -0.49^{*}$) between log (PS) and log (pH/OM) indicates a decrease in PS of these acidic, low-OM soils with increasing pH levels. The percent water-stable aggregate (WSA) >0.20 mm diameter, aggregated clay index (AC) and clay dispersion ratio (CDR) correlated weakly with PS. Conversely, the sealing index (SI) (i.e. the ratio of saturated hydraulic conductivity of an uncrusted to that of a crusted soil) had a strong, inverse relationship with PS ($r = -0.97^{***}$). These relationships indicate that PS measures the slakability (and not dispersibility) of soils. The relationship between PS and erosion (E) was an exponential decay form, $E = 102\,e^{-0.0043PS}$ ($r^2 = 0.98$) and showed that high interrill erosion rates would be expected on soils with PS < 250 ml/10 min. The PS which is simple to measure, is, therefore, a good indicator of structural stability for assessing the potential of these soils to erode.

Keywords: Aggregate stability; Soil structure; Tropics; Structural indices; Soil erosion; Soil properties

1. Introduction

Knowledge of the structural stability of soils and factors that influence it is important in evaluating the crusting/sealing potential of soils, soil permeability, steady-state infiltration rates, soil erosion and seedling emergence and in predicting the capacity of soils to sustain long-term crop production. An attempt has been made in many research projects to evaluate the structural stability of soils using either wet-sieving or simulated raindrop impacts techniques which are laborious and time-consuming to determine (Bruce-Okine and Lal, 1975; Kemper

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and Rosenau, 1986) and always not reproducible (Mbagwu and Bazzoffi, 1998). For a reliable laboratory assessment of aggregate stability, it is desirable to use indices which are inexpensive and straight forward to measure and which yield reproducible results (Mbagwu, 1992).

In Germany, Becher and Kainz (1983) and Kainz and Weiss (1988) developed a methodology for assessing aggregate stability based on the amount of water that percolated through a column of dry soil aggregates. This index, known as percolation stability (PS), is easy to measure and has been reported to correlate significantly with soil erosion measured in the field (Neyer, 1994). The principle behind the determination of PS is that when a dry aggregate suddenly comes into contact with water, the outside wets and water is pulled into it by adhesive forces (matric potential) and during this process the water displaces or compresses the air within the intra-aggregate pores. If the aggregate is being wetted from all sides this leads to compression of the air within these pores, resulting in a build up of pressure. If this pressure is high enough to overcome the cohesive forces holding the aggregate together, the aggregate will break into microaggregates of different sizes and strength (Cernuda et al., 1954; Brewer and Blackmore, 1956). These microaggregates are often displaced downward, blocking the water-conducting pores thereby reducing the amount and rate of water passage through the column of aggregates. Conversely, if the strength of the aggregate is high enough to resist breakdown, the aggregate maintains its integrity and no pore-blocking microaggregates are produced. Consequently water passage through a bed of such aggregates will be higher than that through unstable aggregates. Auerswald (1995) studied in detail the physical factors and processes that influence the PS of top arable soils in Bavaria (Germany) and observed an increase in PS with decreasing pH/OM ratio.

So far no attempt has been made to relate PS to other more familiar indices of stability and land use. Moreover, there is a need to test its applicability on other soils outside the region where it was developed. The objectives of this study were to (i) evaluate the main soil physico-chemical properties that influence the PS of some soils under different tropical landuse systems and (ii) establish empirical relationships between PS and other well known indices of structural stability and simulated rainfall-induced erosion. This will aid in the transferability of this method of assessing structural stability to other areas that have problems with fragile soils.

2. Materials and methods

2.1. Soils and land use

Soil samples were collected from 22 sites in different parts of Nigeria, representing forests, secondary forests, grass pasture, arable and plantation crops with or without tillage and surface mulch cover (Table 1). Nineteen samples were from the Ap horizon, two from the B horizon and one from the C horizon (Table 2). The soils represent the main taxonomic groupings found on the dominant parent materials in Nigeria. This was done to obtain a wide variation in PS and other soil properties thought to influence PS. After air-drying, the soil samples were sieved to obtain the 1–2 mm dry aggregates which were used for all the determinations.

2.2. Determination of percolation stability

Percolation stability (PS) was determined in triplicate as described by Becher and Kainz (1983) and Auerswald (1995). 10 g of the 1–2 mm diameter air-dried aggregates were put in cylindrical, plexiglass tubes of dimensions, 1.5 cm internal diameter and 10.5 cm long. The lower ends of the tubes were covered with a fine wire mesh and 1–2 mm depth of medium size sand grains were placed at the bottom and on top of the aggregates with the aggregates being in direct contact with the sand. The aggregates were packed homogeneously by mechanically dropping the tube 10 times from a height of 2 cm onto a hard surface. Thereafter, deionized water was used to percolate the aggregate column under a hydrostatic pressure head of 20 hPa for 10 min. The amount of water that percolated in 10 min is regarded as the uncorrected PS. The final percolation rate (Pr) (ml/min) was also obtained at the end of 10 min. Since the PS is very much positively influenced by the sand content of soils (which does not imply increase in stability), the measured PS was corrected for total sand (63–2000 μm) in the aggregate thus,

Table 1
Location, classification and land use of the 22 sites studied

Site number	Location	Soil classification[a]	Land use[b]
1	Jos Eutric Regosols		Continuously tilled (CT), unmulched plot planted to maize
2	Abuja	Ferralic cambisols	Mulched, conventionally tilled plot of maize/cowpea intercrop
3	Arochukwu	Haplic nitosols	A 6-year-old puddled paddy rice field
4	Ekwegbe	Ferric acrisols	B-horizon of a soil supporting a >20-year old cashew plantation
5	Udi	Ferric acrisols	C-horizon of a secondary forest soil exposed during road construction
6	Bauchi I	Gleyic vertisols	>15-year-old secondary forest
7	Nsukka I	Plinthic acrisols	>30-year-old pasture of mixed grasses on which cattle graze
8	Njala	Vertic luvisols	CT, unmulched plot of cowpeas grown continuously for 5 years
9	Emene	Haplic nitosols	Unmulched plots of cassava grown continuously for 2 years
10	Nsukka II	Ferric acrisols	>100-year old climax forest vegetation
11	Atani	Eutric gleysols	Floodplain plot of cocoyam/maize/vegetables grown on mounds
12	Owerri	Haplic nitosols	Minimum-tilled cassava plot grown continuously for 3 years
13	Calabar	Haplic ferralsols	>30-year old rubber plantation on which maize/cassava is grown between rows continuously
14	Ezilo	Dystric gleysols	2-year-old, minimum-tilled, mulched plot of cassava/vegetables
15	Iwo	Haplic luvisols	CT plot on which maize has been grown continuously for 5 years
16	Bauchi II	Haplic luvisols	Minimum-tilled plot on which sorghum/soybean have been grown for 4 years
17	Abakiliki	Haplic nitosols	CT plot between alleys of *Leuceneae leucocephala* whose leaves are periodically prunned and incorporated into the topsoil
18	Lau	Gleyic vertisols	CT plot on which sorghum has been grown for 10 years
19	Benin City	Rhodic nitosols	5-year old bush fallow
20	Lafia	Haplic luvisols	Plot of yams from where residues were burnt annualy for 3 years
21	Orlu	Haplic nitosols	B-horizon of a soil on which cassava/maize was grown for 5 years
22	Okigwe	Vertic luvisols	20-year-old secondary forest

[a] FAO/UNESCO classification.
[b] With the exception of Site Nos. 4, 5 and 21, other soil samples were collected from the Ap horizon.

$$\mathrm{PS\,(corrected)} = \frac{\mathrm{PS\,(uncorrected)} \times (100 - \%\mathrm{sand})}{100} \quad (1)$$

The PS data reported here are the corrected values.

2.3. Determination of other indices

The other indices of stability were also measured on the 1–2 mm dry aggregates. The first was water-stable aggregates (WSA) using the single sieve, wet-sieving technique (Mbagwu, 1992). 10 g of the sample were placed on a 0.20 mm sieve and pre-soaked in distilled water for 10 min. Thereafter, the sieve and its contents were oscillated vertically for 20 times along a 4 cm amplitude at the rate of one oscillation/s. The fraction remaining on the sieve was oven-dried at 105°C for 24 h, weighed and corrected for the sand fraction to obtain the proportion of true aggregates (Kemper and Rosenau, 1986). The percent WSA was then computed thus,

$$\mathrm{WSA} = \frac{(\mathrm{Ma} + s - \mathrm{Ms})}{(\mathrm{Mt} - \mathrm{Ms})} \times 100 \quad (2)$$

where Ma + s = mass of the resistant aggregates plus sand (g); Ms = mass of the sand fraction alone (g); and Mt = total mass of the soil sieved (g). For each soil three determinations were made and variations among these determinations for each sample were <2%. The second index was the SI which was determined on two samples per each soil using the procedure of (Pla, 1986). 75 g of the 1–2 mm dry aggregates were packed uniformly into cylindrical PVC tubes, each of inner diameter 5.0 cm and volume, 100 cm^3. The base of each tube was covered with a fine mesh cheese cloth to prevent loss of the soil particles. Each tube was tapped gently on the workbench until the height of soil inside the tube was 3.0 cm, giving a bulk density of approximately 1.27 Mg/m^3.

To induce slaking, sealing and crusting, one set of the samples was subjected to a rainfall intensity of about 75 mm/h (generated as described in Section 2.4)

Table 2
Morphology, particle size distribution and texture[a] of the 22 soils

Soil number	Depth (cm)	Colour (dry)	Total sand (g/kg)	Coarse sand (g/kg)	Fine sand (g/kg)	Very fine sand (g/kg)	Silt (g/kg)	Clay (g/kg)	Texture
1	0–10	7.5YR4/6	73	22	35	16	289	638	C
2	0–20	2.5Y5/2	487	82	291	114	326	187	L
3	0–30	10YR5/6	410	47	258	105	230	360	CL
4	10–30	7.5YR6/8	520	106	369	45	2	478	SC
5	100–150	5YR6/8	818	292	482	44	22	160	CL
6	0–10	2.5Y6/2	342	205	104	33	189	469	CL
7	0–5	10YR4/6	248	93	87	68	134	618	C
8	0–10	2.5Y5/2	450	303	120	27	312	238	L
9	0–15	10YR7/8	376	18	245	113	182	442	CL
10	0–20	5YR4/8	701	323	334	44	26	273	SCL
11	0–20	2.5Y6/4	488	95	143	250	100	412	SC
12	0–20	10YR4/6	855	117	727	11	0	145	SL
13	0–15	10YR5/4	800	297	490	13	0	200	SL
14	0–20	10YR7/6	433	19	69	345	450	117	L
15	0–20	7.5YR6/6	615	238	337	40	111	274	SCL
16	0–10	10YR5/3	614	532	63	19	221	165	SL
17	0–10	7.5YR6/4	291	172	37	82	526	183	SiL
18	0–15	2.5Y5/7	165	55	73	37	228	607	C
19	0–15	7.5YR4/6	780	145	623	12	33	187	SL
20	0–10	10YR5/4	833	80	668	85	90	77	LS
21	10–30	5YR5/8	684	95	560	29	0	316	SCL
22	0–20	2.5Y5/2	152	84	56	16	173	675	C
CV %	–	–	50	97	64	94	77	60	–

[a] Total sand = 63–2000 μm; coarse sand = 630–2000 μm; fine sand = 100630 μm; very fine sand = 63–100 μm; silt = 2–63 μm; clay = < 2 μm.
C – Clay.
L – Loam.
CL – Clay loam.
SC – Sandy clay.
SL – Sandy loam.
SCL – Sandy clay loam.
SiL – Silty loam.
LS – Loamy sand.

for 2 min and then allowed to air-dry. After drying, the exposed soil surfaces inside the rings were observed to have formed thin layers of crusts. Another set of the samples which was not exposed to simulated rainfall was used as the control (i.e. the uncrusted surface). Thereafter, saturated hydraulic conductivity (K_s) was measured on each of the crusted and control samples using the constant head permeameter method (McIntyre, 1958; Klute, 1965). The ratio of K_s of the uncrusted sample to that of the crusted sample was used as the SI. Higher values indicate greater tendency for the soils to slake when in contact with water which imply weak structural stability. Variation among duplicate determinations for each soil was <10%.

The third index was a colloidal (microaggregate) stability index known as the aggregated clay index (AC). In one set, 10 g of the dry, 1–2 mm aggregates were treated with sodium dithionite–citrate–bicarbonate (DCB) to remove Fe and Al oxides before determining the amount of clay. In another set, 10 g of the aggregates which were not treated with DCB were used to determine the water-dispersible clay (WDC). Clay was determined by weighing separately, the DCB-treated and untreated aggregates into 250 ml plastic bottles, adding 200 ml distilled water and shaking end-over-end for 16 h. The soil suspension was quantitatively transferred into a 1 l graduated cylinder. After the flask and its contents were filled to 1 l with distilled water, it was further agitated end-over-end 20 times and then allowed to settle for 8 h. Thereafter, a pipette was used to determine the amount of clay in suspension (Kamara et al., 1992). The difference between the total (DCB) clay and the WDC defines the AC. Higher values indicate greater colloidal stability. Three measurements per soil sample were made and variation within each soil was <6%.

2.4. Measurement of interrill soil loss using simulated rainfall

Two measurements per soil sample were made as follows: a known quantity of the dry, 1–2 mm aggregates was packed into boxes to a density of approximately 1.25 ± 0.15 Mg/m^3 and then equilibrated at 0.01 MPa matric potential (field moisture capacity) with distilled water. Each box has the following dimensions: length, 26 cm; width, 10 cm and height, 10 cm.The inner surfaces of these boxes were lined with a metal sheet to a depth of 2 cm below the surface. The metal sheet projected 1 cm outside the box to form a groove to channel the sediment to a collecting beaker. Each box was inclined at a slope of 5%.

The rainfall simulator was a modified version of that described by Bertrand and Parr (1961) in which a mariotte bottle technique was used to supply water at a constant pressure head from a large reservoir to a chamber fixed with the raindrop formers made from plastic hypodermic needle caps. The rainfall simulator generated raindrops, each 5.0 mm in diameter, falling through a height of 1.0 m for 30 min and at an intensity of 75 mm/h. This intensity was uniform over the entire 260 cm^2 area. The sediments and run off were collected in beakers and dried in an oven at 105°C for 96 h to ensure complete evaporation of water before recording the sediment mass. Variation between the duplicate measurements was <17%.

Table 3
Some chemical properties of the 22 soils

Soil number	OM (g/kg)	pH (0.01M $CaCl_2$)	pH/OM	TEB[a] (Cmol (+)/kg)	CEC (Cmol (+)/kg)	ESP[b]	Fe_d[c] (g/kg)	Fe_o (g/kg)	Al_d (g/kg)	Al_o (g/kg)
1	22.6	5.1	2.26	11.98	23.0	1.09	45.2	3.16	4.75	1.77
2	20.0	4.6	2.30	7.18	11.5	2.43	3.8	0.44	0.36	0.35
3	22.2	3.9	1.76	1.96	33.0	0.52	13.9	3.46	3.76	1.61
4	7.1	4.4	6.20	0.55	6.5	2.62	15.5	0.22	2.98	0.88
5	1.2	4.2	35.0	0.52	3.5	4.57	1.4	0.05	0.25	0.07
6	12.9	6.6	5.12	25.77	29.0	1.38	8.2	1.04	0.56	0.46
7	50.0	3.7	0.74	4.13	18.5	1.08	109.3	1.64	9.77	2.54
8	10.2	4.8	4.71	10.8	73.5	1.63	2.9	0.97	0.36	0.29
9	6.6	3.4	5.15	4.17	7.5	2.00	53.1	0.78	3.69	0.62
10	23.3	3.4	1.46	0.54	8.5	1.76	26.4	1.47	1.97	0.93
11	35.3	4.0	1.13	11.17	25.0	1.80	13.8	6.79	1.16	0.80
12	11.4	4.1	3.60	1.69	3.5	4.86	4.3	0.37	1.23	0.40
13	18.3	4.0	2.19	0.73	7.0	2.43	4.4	1.35	1.26	0.61
14	8.8	4.4	5.00	3.30	6.5	3.23	9.3	1.81	1.57	0.56
15	8.6	5.4	6.28	3.36	6.5	2.62	12.1	0.84	1.28	0.48
16	20.5	5.7	2.78	9.35	11.0	8.80	2.9	0.46	0.40	0.26
17	20.9	4.4	2.11	3.59	10.0	3.00	101.7	1.00	0.63	0.54
18	12.6	6.1	4.84	33.89	36.5	2.08	1.9	0.12	0.81	0.71
19	33.3	4.2	1.26	2.86	8.5	3.18	15.3	0.92	1.99	1.01
20	7.1	5.2	7.32	3.16	4.5	4.00	2.0	0.16	0.22	0.16
21	8.6	3.9	4.53	0.81	6.0	7.17	14.6	0.56	1.70	0.59
22	46.5	5.8	1.25	38.93	44.0	0.77	6.2	2.27	7.39	1.05
CV %	69	19	141	132	79	69	142	100	109	76

[a] TEB – total exchangeable bases.
[b] ESP – exchangeable sodium percentage.
[c] Fe_d, Al_d – Na-dithionite-citrate-bicarbonate extractable; Fe_o, Al_o – ammonium oxalate extractable.

Table 4
Structural stability of the soils as evaluated by different indices[a]

S/No	Location	Soil loss (E), g	PS (ml/10 min)	Final Pr (mm)	WSA >0.20	SI	AC	WDC
1	Jos	77	79	6	33	4.1	51.5	12.3
2	Abuja	37	241	33	12	1.6	10.6	8.1
3	Arochukwu	79	74	7	20	4.2	20.3	15.7
4	Ekwegbe	46	155	74	17	3.1	38.5	9.1
5	Udi	88	46	78	1	5.1	13.8	2.5
6	Bauchi 1	17	414	54	42	1.2	22.8	24.1
7	Nsukka 1	9	591	90	5	1.1	48.7	13.1
8	Njala	89	34	7	12	5.1	12.6	11.2
9	Emene	84	64	8	18	4.7	35.6	8.6
10	Nsukka 2	13	513	105	21	1.1	16.0	11.3
11	Atani	84	61	4	30	4.6	27.4	13.8
12	Owerri	50	148	101	18	3.2	7.6	6.9
13	Calabar	41	183	100	33	2.1	7.6	12.4
14	Ezilo	38	240	22	5	1.6	9.0	2.7
15	Iwo	55	138	26	22	3.2	8.2	19.2
16	Bauchi 2	65	99	37	7	4.1	7.5	9.0
17	Abakiliki	29	279	70	11	1.4	9.4	8.9
18	Lau	87	51	1	36	5.2	22.5	38.2
19	Benin	20	342	93	26	1.3	10.5	8.2
20	Lafia	56	140	72	10	3.2	2.9	4.8
21	Orlu	83	64	20	25	4.7	13.5	18.1
22	Okigwe	28	276	21	73	1.4	30.4	37.1
	CV%	50	81	78	73	49	71	68

[a] PS – percolation stability; WSA = water-stable aggregates.
SI – slaking index.
AC – aggregated clay.
WDC – water-dispersible clay.

2.5. *Determination of other soil properties*

Some intrinsic soil properties which were thought to influence PS were determined as follows: particle size distribution by the pipette method after pretreatment with DCB, organic carbon (OC) by dry combustion and converted to organic matter (OM) by multiplying by a factor of 1.724 and pH in 0.01M $CaCl_2$ suspension. Cation exchange capacity (CEC) was measured by NH_4^+ saturation, followed by displacement and titration of NH_3 collected in boric acid. After leaching the soils with 1N ammonium acetate solution, the Ca and Mg in the leachate were determined with atomic absorption meter and Na and K by flame photometer. The exchangeable sodium percentage (ESP) was computed as the ratio of exchangeable Na^+ to the CEC. These properties are summarized in Tables 2 and 3 whereas the structural properties are given in Table 4.

3. Results and discussion

3.1. *Physico-chemical and structural properties of the soils*

The intrinsic properties of the soils in Tables 2 and 3 show high variability in all properties except the pH. Eight FAO textural classes (viz, clay, loam, clay loam, sandy clay, sandy loam, sandy clay loam, silty loam and loamy sand) are represented in these soils. The PS of the Bavarian soils used by Auerswald (1995) varied from 15 ml/10 min to 900 ml/10 min whereas those used in the present study ranged from 34 ml/10 min to 591 ml/10 min. Hence, the Bavarian soils covered a wider range in stability than the Nigerian soils. This should be expected since 113 soil samples were used by Auerswald (1995) as against only 22 samples used in the present study. Also compared with the Bavarian soils, the soils used for this study have narrower ranges in OM and pH (in $CaCl_2$). Most of the soils have low total exchangeable bases (especially exchangeable Ca + Mg) which is responsible for their high acidity. The ESP is generally low and indicates that the dispersibility of these soils may not be due to the presence of Na^+ on the exchange sites. The concentration of Fe and Al not extractable with oxalate, which indicates good crystallinity (i.e. DCB-extractable Fe and Al − NH_4-oxalate extractable Fe and Al) are higher than those of the oxalate-extractable (low crystallinity) Fe and Al, with the latter constituting between 1.5% and 19.3% of the total Fe and between 14.2% and 86.9% of the total Al.

Among the structural properties shown in Table 4, the highest coefficients of variability (CV) among the soils occurred in PS (81%) followed by Pr (78%) and WSA>0.02 mm (73%) whereas the lowest CV were obtained in the SI (49%) and soil loss data, *E* (50%). Percolation stability varied between 34 and 591 ml/10 min. The soil with the lowest PS, no. 8 also had the highest soil loss (*E*), whereas the soil with the highest PS, no. 7 lost the smallest amount of soil.

With the exception of soil no. 1, all the other soils had <50% of their total clay in aggregated form. This indicates low colloidal stability. On the other hand, the absolute values of WDC are generally low which implies high stability. If however, the WDC is expressed as a percent of the total clay, 15 out of the 22 soils have >40% of their clay dispersible, which places them in the high-to-very high dispersible class (Mbagwu, 1986). This and the values of WSA > 0.20 mm (which are below 45%) indicate that these soils are generally weakly-structured.

3.2. Percolation stability in relation to land use

As shown in Table 5, climax and secondary forests, bush fallows, mulched and minimum-tilled plots had rapid PS (>250 ml/10 min) whereas paddy rice fields, unmulched, continuously cropped plots and subsoils had low PS (<150 ml/10 min). Moderate PS values (250–150 ml/10 min) were observed on soils in long-term rubber plantation, and mulched conventionally or minimally tilled plots. Expectedly the highest PS value was obtained on a >30-year-old grass pasture which also had the highest organic matter (OM) content, followed closely by a >100-year old climax forest (513 ml/10 min), whereas the lowest values (34–51 ml/10 min) were obtained on continuously cropped, conventionally-tilled plots and on a sample from the C-horizon of a sandy soil, low in OM.

Even though none of the PS values of the three subsoil samples (Nos. 4, 5, 21) fell within the rapid class (Table 5), it is also evident that the PS of several topsoil samples were lower than those of these subsoil samples. For example, the lowest PS of 34 ml/10 min was obtained from a topsoil sample and the PS of topsoil sample no. 9 (64 ml/10 min) was the same as that of the subsoil sample No. 21. Hence PS of these soils was influenced more by land use history than the location in the soil profile from where the sample was collected.

3.3. Percolation stability in relation to intrinsic soil properties

Table 6 shows the correlation between PS and other soil properties. The highest coefficients of correlation

Table 5
Summary of the percolation stability (PS) classes in relation to land use[a]

PS class	Range in values (ml/10 min)	Site numbers included[b]	Dominant land use types[c]
Rapid	>250	6, 7, 10, 17, 19, 22 (27.3%)	Forests, secondary forexts, bush fallows, mulched, minimum-tilled plotes, pastures
Moderate	250–150	2, 4, 13, 14 (18.2%)	Mulched, CT and unmulched, MT, plots, plantations
Slow	<150	1, 3, 5, 8, 9, 11, 12, 15, 16, 18, 20, 21 (54.5%)	Paddy field, unmulched plots secondary forest subsoil, continuously cropped plots

[a] These are relative rather than absolute classes.
[b] The values in parenthesis are the percentage of sites included in all the sites.
[c] CT – conventionally-tilled; MT – minimum-tilled.

Table 6
Correlation between percolation stability (PS) and intrinsic soil properties

Independent variables[a]	Correlation coefficient (r)	Significant level[*]
Silt	0.01	NS
Clay	0.09	NS
WDC	0.03	NS
OM	0.55	*
pH	−0.09	NS
OM/pH	−0.31	NS
CEC	0.05	NS
ESP	−0.29	NS
Fe_d	0.46	*
Fe_o	−0.06	NS
Al_d	0.40	NS
Al_o	0.42	NS
$Fe_d + Al_d$	0.52	*

[a] WDC – water-dispersible clay, d – dithionite-citrate–bicarbonate extractant, o – ammonium oxalate extractant.
ESP – exchangeable sodium percentage.
CEC – cation exchange capacity.
[*] Significant at $p < 0.05$.
NS – not significant.

were obtained with OM ($r = 0.55^*$) followed closely by total Fe + Al ($r = 0.52^*$) and total Fe ($r = 0.46^*$). Also total Al and oxalate-extractable Al had positive correlations of 0.40 and 0.42, respectively, with PS (which are significant at $p < 0.10$). Auerswald (1995) also reported highly significant, positive correlation between PS and OM for some Bavarian soils but contrary to the results of this study, did not obtain significant correlations between PS and Fe and Al oxides. This is probably because the soils used for this study are generally older, more weathered and contain higher amounts of Fe and Al than the soils used by Auerswald (1995). The mechanisms by which OM enhances structural stability have been summarized by Oades (1984). Shainberg et al. (1987) also observed that high concentrations of Fe and Al oxides were responsible for high saturated hydraulic conductivity of a sandy loam soil.

The texture parameters (silt and clay) and pH had low, non-significant correlations with PS. The regression between log (PS) and log (pH/OM) was

$$\mathrm{Log}\,(\mathrm{PS}) = 2.39 - 0.48 \times \mathrm{Log}\,(\mathrm{pH/OM}) \qquad (3)$$

and explained about 24% of variation in PS. Such negative correlations between PS and pH/OM were also reported by Neyer (1994) and Auerswald (1995). Several authors (Saurez et al., 1984; Miller and Baharuddin, 1986; Levy et al., 1993) have associated decrease in water permeability of soils as pH increased to Na-induced dispersed clay particles which blocked the pore spaces. In this study however, the ESP values are generally low and the correlation between PS and ESP ($r = -0.29$) is weak. Hence, the tendency for PS to decrease as pH increases cannot be associated with the presence of Na^+ on the soil exchange site.

Roth and Pavan (1991) reported that on highly weathered, acidic, low-OM Oxisols in Brazil lime-induced increase in pH led to structural instability and increased WDC and erosion. Benito and Diaz-Fierros (1992) also observed that as the pH of OM-rich soils increased, the stability of their aggregates decreased. These reports indicate very strongly that liming to reduce Al toxicity or increase the contents of Ca and Mg in soils should be done with caution since it may lead to structural collapse.

3.4. *Percolation stability in relation to other indices of structural stability*

As shown in Table 7, the highest correlation between PS and other measured structural properties was obtained with the SI, followed by the final Pr. The regression equation which explained the highest variation in PS (94%) was

$$\mathrm{Log}\,(\mathrm{PS}) = 2.72 - 1.37 \times \mathrm{Log}\,(\mathrm{SI}). \qquad (4)$$

Table 7
Linear relationship of the form: $Y = a + bX$ between percolation stability (PS, Y) and other structural indices (X)

Independent (X)	Correlation	Intercept	Slope
Pr	0.58^*	78.15	2.44
WSA > 0.20	0.05	179.98	0.58
SI	-0.80^{***}	435.16	−83.07
AC	0.15	158.61	1.73
CDI	0.02	185.92	0.42

[a] Pr – final percolation rate.
WSA > 0.20 mm – water-stable. aggregates > 0.20 mm in diameter.
SI – sealing index.
AC – aggregated clay.
CDI = clay dispersion index.
[*]Significant at $p < 0.05$, [***]significant at $p < 0.001$.
NS – not significant.

It shows that soils which slake easily will have low PS.The indices which are used to express the stability (or dispersibility) of clay in water (i.e. the aggregated clay index, AC and the clay dispersion ratio, CDR) correlated very weakly with PS. This is a confirmation of the assertion of Auerswald (1995) that PS measures slaking potential and not dispersibility of soil aggregates and shows that the mechanisms governing the two processes are different.

The percent WSA, which has been used by many researchers to assess the relative susceptibility of soils to erode (Bryan, 1968), correlated weakly with PS. This is a reflection of the fundamental differences between the procedures used to determine the two stability indices. The percent WSA index measures the size and stability of aggregates produced by the scouring action of water, whereas the PS measures the effect of pore-blocking, slaked particles and microaggregates on water movement through a soil column or a bed of aggregates.

The regression between PS and the final Pr is

$$\mathrm{Log(PS)} = 1.58 + 0.40 \times (\mathrm{LogPr}) \quad (5)$$

and explained just 43% of variation in PS. One would have expected a stronger correlation between PS and Pr than this. A possible explanation for this low correlation is that the slaking process varies between soils not only in extent of reducing the aggregate size but also in the time required for a soil to slake. A low PS could, therefore, be the result of a quickly slaking soil which does not slake completely and thus still retains a medium Pr. It could, however, also be the result of a slowly but completely slaking soil exhibiting a low Pr (Auerswald, 1995).

3.5. Simulated rainfall erosion in relation to percolation stability and sealing index

Soil loss after simulated rainfall (E) decays exponentially with PS,

$$E = 102\mathrm{e}^{[-0.0043\times \mathrm{PS}]} \quad (6)$$

and explained 98% variation in E. From Fig. 1, as PS decreased from about 250 ml/10 min to 30 ml/10 min, E increased linearly from about 35 g to 89 g. This range covers 73% of the soils that are highly erodible. Six out of the 22 soils (i.e. 27%) that lost <30 g of the soils during erosion represent those with high (>270 ml/10 min) PS. The Pr explained just about 40% of variation in E because similar to PS, E is the result of a longer time span and a large E could be the result of a slowly but completely slaking soil or of a quickly slaking soil which produces only larger microaggregates as observed by Auerswald (1995).

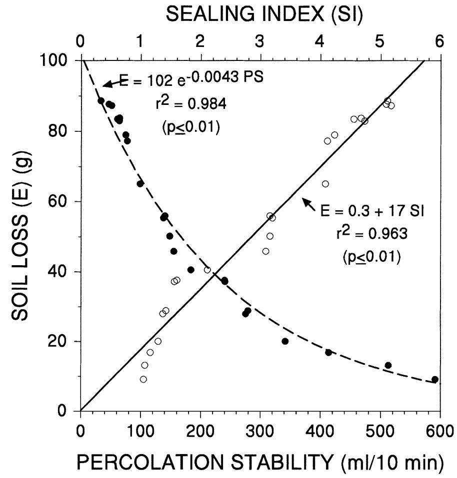

Fig. 1. Relationship between simulated E, PS and SI.

The regression equation between SI and E is

$$E = 0.28 + 17(\mathrm{SI}) \quad (7)$$

This linear relationship explained 96% of variation in E. Since the higher the SI, the more weakly structured the aggregates are, it is reasonable to assume from these results that as the aggregates slake, the particles migrate and either seal the intra-aggregate or block the inter-aggregate pores. This will reduce the rate of water percolation through the soil, leading to accelerated runoff and erosion. Some authors (e.g. Morin et al., 1981; Bradford et al., 1987; Miller, 1987) made similar observations with temperate soils From Eq. (4), soils with high SI also have low PS and from Eq. (6) those with low PS have high erosion rates. Hence soil management practices that decrease the tendency of soils to slake will reduce erosion rates. Neyer (1994) and Kainz and Weiss (1988) also obtained high correlation between PS and erosion and Auerswald (1993) showed that reduction in soil erosion rates was due to decrease in slaking.

4. Conclusions

Results from this research show that land use influenced PS more than the intrinsic soil properties. Also, whereas no single intrinsic soil property had strong influence on the PS of these soils, PS values tended to increase with increasing the OM, Fe and Al contents. Similar inverse relationship noted between PS and SI suggests that the same processes influence them. Both the PS and SI can be used to evaluate the potential interrill erodibility of soils but considering the ease of measurement, PS is more useful and reliable than SI for quick assessment of soil erodibility.

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